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# Integration of a 5-axis Spline Interpolation Controller in an Open CNC System

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**Abstract**

A 5-axis controller with curve interpolation function is developed to satisfy high-speed and high-precision computer numerical control (CNC) machining of machine parts with complex shapes in the authors-devised open CNC system. The instruction format of this interpolation method and the generation procedure of the numerical control (NC) files are introduced. The interpolation curves of both position vectors and orientation vectors constructed by the controller are $C^2$ continuous and independent of machine tool kinematics. The controller fits in with any 5-axis machine tools by configuring the related kinematics transformation module. The position curve is to be discretized in realtime using a truncated Taylor series expansion. Coordinated motions of linear axes and rotary axes are achieved by relating the orientation curve parameter to the position curve parameter in the machining process. The performance of the proposed controller is demonstrated by a practical example.

*Keywords:* numerical control systems; sculptured surfaces; 5-axis machining; motion control; curve interpolation

## 1. Introduction

Nowadays, the machining of workpieces with sculptured surfaces is of great importance to a variety of industries, such as aerospace, automobile, steamboat, cutter-producing, and die-making industry, just to name a few[1-3]. These workpieces are widely machined by 5-axis machine tools with linear interpolation function, but this mode of processing has disadvantages as follows: ①a large numerical control (NC) file needed to transfer into a controller; ②low efficiency in machining for high-frequency acceleration and deceleration; ③poorer quality of machined part surfaces. Today, the curve interpolation function has become a standard configuration of top grade computer numerical control (CNC) machine tools thanks to the edge over the linear interpolation. For example, FANUC and SIEMENS have developed curve interpolation functions and non-uniform rational B-spline (NURBS) interpolation[4] for their top grade CNC systems. Nevertheless, their realization methods have not yet been made public. Therefore, research on curve interpolation methods for 5-axis machining has become a hotspot in CNC technology. A number of researchers[5-9] have long devoted themselves to the curve interpolation for NC machining. These articles suggest that curves be used to describe tool path to reduce the appearance of tangency discontinuities along the machining path produced by the linear interpolation. However, the calculated tool path is only suitable for a dedicated machine tool following a certain kinematics. New complex calculation should be repeated once the machine tool has been changed. In addition, in 5-axis machining, maintaining a constant feedrate along the position curve and a constant angular velocity along the orientation curve as it used to be in common would result in uncontrollable effective federate[10].

This article presents a curve interpolation format suitable for 5-axis machine tools. Modules of a 5-axis controller with curve interpolation functions of this format are developed for the control of 5-axis machine tools in the authors-devised open CNC system. Tool path calculated by the computer aided manufacture (CAM) system or other programming systems is directly implanted into the curve interpolation controller for it can perform all tool path implementation in the workpiece system. Because the inverse kinematics transformation required by 5-axis machining is carried out by the NC controller itself, the NC programming becomes easier and any work related to machine tool

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changes would be spared. In machining process, coordinated motion is achieved by correlating the orientation curve parameters to the position curve parameters, which would result in controllable effective feedrate and high machining accuracy.

## 2. Format of 5-axis Spline Interpolation and NC Codes Generation

Machining of machine parts requires generating tool paths, which determine the motions of tool with respect to the part to be cut[11-12]. 3-axis tool paths are represented by a set of Cartesian position vectors, each defining the location of the tool with respect to the part. Orientation of the tool must also be defined for 5-axis tool paths. Consequently, a 5-axis tool path is represented by a set of vectors which can be classified into position vectors and orientation vectors (unit vectors).

Fig.1 shows the 5-axis spline interpolation command format. The program segment begins with G05.0. In Fig.1, Values after X, Y, and Z are three components of one position vector in a tool path. Values after U, V, and W are components of the related orientation vector. Values after F is the feedrate information. Scalar components of these vectors are all coordinate values in a machine part coordinate system of the part.

```
G05.0 X_ Y_ Z_ U_ V_ W_ F_;
      X_ Y_ Z_ U_ V_ W_;
      X_ Y_ Z_ U_ V_ W_;
      X_ Y_ Z_ U_ V_ W_;
      X_ Y_ Z_ U_ V_ W_;
      …
```

Fig.1 5-axis spline interpolation command format.

The generation of program file of this format processed by the NC controller can be divided into four steps.

(1) Designing surfaces of the part by using a computer aided design (CAD) system.

(2) Calculating the machine-tool trajectory according to a predetermined machining strategy. First, calculate a tangent location of the tool on the part surface. Later, calculate an actual tool path from a set of successive tool positions belonging to the theoretical tool path. The calculated curve is a B-spline curve, which is deviate from the theoretical one in the range of machining tolerances caused by minimizing the information input in the curve controller with the possibly least sample positions[13]. The set of tool positions thus acquired serves as tool path information needed by the NC unit. Interference checking and modifying cutter location are demanded throughout the whole process.

(3) Calculating the tool path perpendicular to the feed direction according to the allowable maximal scallop height.

(4) NC programming by translating all the sets of tool position vectors and their corresponding orientation vectors into the spline interpolation format (see Fig.1).

Note that a tool trajectory calculated for linear interpolation is not a good support for an expected accurately designed tool path for the spline interpolation because the position and orientation curves constructed in the following might present high-frequency oscillation and arcs of minor lengths which are unacceptable by the NC unit. The tool path appears to be a $C^2$ curve generated by interpolation of a set of particular positions, and the divergence of the calculated curves from the ideal one is smaller than the machining allowances. In order to simplify the work of NC controller, the number of tool path points must be minimal in-so-far as the part tolerances are met[13].

## 3. Structure of 5-axis Controller

The authors have developed an open architecture of software-CNC system on personal computer (PC) according to the open modular architecture controllers (OMAC). For more details pertinent to the open CNC system, refer to Ref.[14]. In order to perform CNC machining with the proposed spline interpolation method, special modules have been developed to construct a motion controller for CNC machine tools in the software module library of the open CNC system.

Fig.2 shows the structure of the spline interpolation controller for 5-axis machining. The human machine interface (HMI) module fulfils functions of setting and modifying system parameters, entering and editing NC process programs, and displaying diagnosis information. The task coordinator module is responsible for task assignment, as well as coordination and scheduling of modules. The task generator module (the code interpreting module) checks vocabulary and grammar of NC process programs, sorts and extracts all information in the programs, and generates logical control instructions and motion segment instructions containing motion information. The task generator module will realize cutter compensation as well. The axis

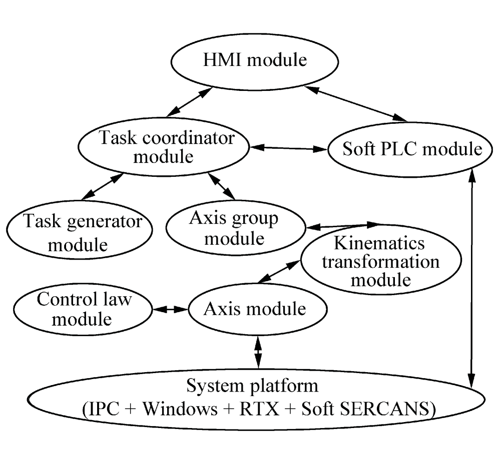


Fig.2 Structure of spline interpolation controller for 5-axis machining.

group module serves to interpolating and exerting control of acceleration and deceleration. The kinematics transformation module receives position information from the axis group module and converts points to coordinate system of machine tools. The axis module receives instructions from the kinematics transformation module and feedback information outside, calls for servo control laws designated by users to carry out position control and speed control, and finally sends control signals to executive units. The soft programmable logical controller (PLC) module exchanges information with the task coordinator module to control input/output devices outside.

The ability to interchange information between the controller and the servo system which are included in the CNC system has direct effects on the CNC system[15-16]. The only international standard applied to commutations between the CNC and the digital servo system is the serial realtime communication system (SERCOS) digital interface which has found wide application.

The NC program is then implanted into the controller. Finally, the controller computes the axis target positions in the next interpolation period based on a given algorithm. Fig.3 shows the procedure of data processing.

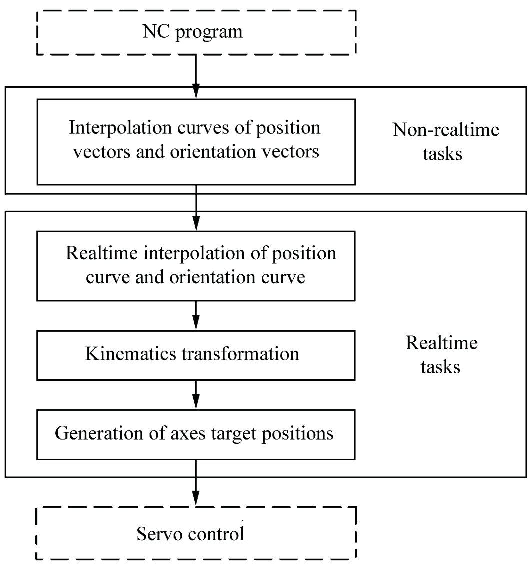


Fig.3 Data processing procedure.

## 4. Translations and Spline Interpolations in Motion Controller

### *4.1. Translations of NC program*

When the NC program is input, it is translated by the task generator module. Special data structures (described in C++) for the task generator module are developed to store information in the NC program. The data structures are as follows.

```
typedef enum {LINE, DNURBS, CSCURVE}
// defining motion segment type
typedef structure cscurve1_struct{
double start_rate, traverse_rate, end_rate;
// feed rate of the motion segment
double *povecx, *povecy, *povecz;
// array for storing coordinates of position vectors
double *rovecx, *rovecy, *rovecz;
// array for storing coordinates of orientation vectors
...
} cscurve1;
typedef structure cscurve2_struct{
double start_rate, traverse_rate, end_rate;
// feed rate of the motion segment
double *u;   // array for storing knot vector
double *d;   // array for storing control points
double *pa1, *pa2, *pa3, *pa4,*pa5;
// array for storing parameters of sphere curves
...
} cscurve2;
typedef structure singleStep_struct{
SingleStep_TYPE singleStep_type;
line line_struct;
// structure for storing linear motion information
dnurbs dnurbs_struct;
// structure for storing double NURBS motion information
cscurves2 cscurve2_struct;
// structure for storing cscurve motion information
} singleStep;
Typedef std::deque<singleStep> singleStep_deque;
```

The information in the “cscurve2” structure is converted into the axis group module for interpolation.

### *4.2. Interpolation curve for position and orientation vectors*

Position and orientation vectors in the structure “cscurve1” are further treated by the task generator module. A B-spline position curve through the set of position vectors and a $C^2$ sphere curve through orientation vectors are obtained.

(1) $C^2$ B-spline curve for position vectors

Let the position vectors be $\{\boldsymbol{p}_0, \boldsymbol{p}_1, \cdots, \boldsymbol{p}_n\}$. The non-uniform cubic B-spline curve $\boldsymbol{p}(u)$ is calculated with the set of position vectors resulting in $\boldsymbol{p}_i \in \boldsymbol{p}(u)\,(i = 0,1,\cdots,n)$. At first, the knot vector of $\boldsymbol{p}(u)$ is calculated by using the method of standard-chord-length parameterization, which has come in broad use in computer-aided geometric design (CAGD). The resultant knot vector is $\boldsymbol{U}$ ($\boldsymbol{U} = [u_0 \quad u_1 \quad \cdots \quad u_{n+6}]$), in which $[u_3, u_{n+3}]$ belongs to [0, 1], $u_0 = u_1 = u_2 = u_3 = 0$ and $u_{n+3} = u_{n+4} = u_{n+5} = u_{n+6} = 1$. The control points for $\boldsymbol{p}(u)$, $\boldsymbol{d}_j\,(j = 0,1,\cdots,m)$, where $m$ is equal to $n+2$, can be achieved as follows.

$$\begin{bmatrix} a_1 & b_1 & c_1 & & & \\ a_2 & b_2 & c_2 & & & \\ \ddots & \ddots & \ddots & & & \\ & & & a_{m-2} & b_{m-2} & c_{m-2} \\ & & & a_{m-1} & b_{m-1} & c_{m-1} \end{bmatrix} \begin{bmatrix} \boldsymbol{d}_1 \\ \boldsymbol{d}_2 \\ \vdots \\ \boldsymbol{d}_{m-2} \\ \boldsymbol{d}_{m-1} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e}_1 \\ \boldsymbol{e}_2 \\ \vdots \\ \boldsymbol{e}_{m-2} \\ \boldsymbol{e}_{m-1} \end{bmatrix} \tag{1}$$

where

$$a_i = \frac{(\Delta_{i+2})^2}{\Delta_i + \Delta_{i+1} + \Delta_{i+2}}$$

$$b_i = \frac{\Delta_{i+2}(\Delta_i + \Delta_{i+1})}{\Delta_i + \Delta_{i+1} + \Delta_{i+2}} + \frac{\Delta_{i+1}(\Delta_{i+2} + \Delta_{i+3})}{\Delta_{i+1} + \Delta_{i+2} + \Delta_{i+3}}$$

$$c_i = \frac{(\Delta_{i+1})^2}{\Delta_{i+1} + \Delta_{i+2} + \Delta_{i+3}}$$

$$\boldsymbol{e}_i = (\Delta_{i+1} + \Delta_{i+2})\boldsymbol{p}_{i-1}$$

$$\Delta_i = u_{i+1} - u_i,\ i = 2, 3, \cdots, m-2$$

$a_1$, $b_1$, $c_1$, $\boldsymbol{e}_1$ and $a_{m-1}$, $b_{m-1}$, $c_{m-1}$, $\boldsymbol{e}_{m-1}$ can be found in Ref.[17]. $\boldsymbol{d}_1$, $\boldsymbol{d}_2$, $\cdots$, $\boldsymbol{d}_{m-1}$ can be calculated with Eq.(1). $\boldsymbol{d}_j\,(j = 0,1,\cdots,m)$ will be confirmed by supposing $\boldsymbol{d}_0 = \boldsymbol{p}_0$ and $\boldsymbol{d}_m = \boldsymbol{p}_n$. With knot vector $\boldsymbol{U}$ and control points $\boldsymbol{d}_j\,(j = 0,1,\cdots,m)$, the NURBS interpolation curve $\boldsymbol{p}(u)$ is confirmed.

(2) $C^2$ sphere curve for orientation vectors

Let the orientation vectors be $\{\boldsymbol{q}_0, \boldsymbol{q}_1, \cdots, \boldsymbol{q}_n\}$; the orientation curve through orientation vectors must lay on the surface of a unit sphere since orientation of the tool is defined by a unit vector. Let the NURBS expression of the unit sphere be $\boldsymbol{S}(u,v)$. After inverting, the following equation is achieved

$$\left.\begin{array}{l} \begin{cases} u = \dfrac{(x+y) - \sqrt{x^2 + y^2}}{4x} & y > 0 \\ u = \dfrac{(3x+y) + \sqrt{x^2 + y^2}}{4x} & y \le 0 \end{cases} \\ v = \dfrac{z + 1 - \sqrt{1 - z^2}}{2z} \end{array}\right\} \tag{2}$$

By substituting $\boldsymbol{q}_i\,(i = 0,1,\cdots,n)$ into Eq.(2), $\{\boldsymbol{r}_i\}_{i=0}^n$ ($\{\boldsymbol{r}_i\}_{i=0}^n = \{u_i, v_i\}_{i=0}^n \subset \mathbf{R}^2$) is calculated. The B-spline interpolation curve $\boldsymbol{r}(w)$ through $\boldsymbol{r}_i\,(i = 0,1,\cdots,n)$ can be achieved by the above-mentioned adopting methods. Orientation curve $\boldsymbol{q}(w)$ which is of $C^2$ continuity through orientation vectors can be achieved by substituting $\boldsymbol{r}_u(w)$ and $\boldsymbol{r}_v(w)$ into $\boldsymbol{S}(u,v)$.

## 5. Realtime Interpolator and Kinematics Transformation

### 5.1. Realtime interpolation operation

The task of realtime interpolation is to calculate the parameter $\lambda(k+1)$ in the next interpolation period based on the corresponding parameter $\lambda(k)$ of the current interpolation, where $\lambda$ is the parameter of position interpolation curve $\boldsymbol{p}(\lambda)$. This is a realtime job, and it is treated by the axis group module. Let the position curve be $\boldsymbol{p}(\lambda)$ and the orientation curve $\boldsymbol{q}(w)$. The time function is a parameter of $\boldsymbol{p}(\lambda)$ with $\lambda(t_k) = \lambda_k$ and $\lambda(t_{k+1}) = \lambda_{k+1}$. The first order approximation of interpolation algorithm defined by Eq.(3) is achieved by using a truncated Taylor series expansion.

$$\lambda_{k+1} = \lambda_k + \frac{V(\lambda_k) \cdot T_\mathrm{s}}{\left\| \dfrac{\mathrm{d}\boldsymbol{p}(\lambda)}{\mathrm{d}\lambda} \right\|_{\lambda = \lambda_k}} \tag{3}$$

where $V(\lambda_k)$ might be the feedrate command, the specified speed profiles of ACC/DEC, or any required speed in a general machining process[18-20], $T_\mathrm{s}$ is interpolation period of the controller. By substituting $\lambda_{k+1}$ into $\boldsymbol{p}(\lambda)$, the position vector in the next interpolation period can be found out.

Maintaining an identical feedrate along the position and the orientation curves would result in uncoordinated motion in 5-axis machining due to differences in lengths of the two curves. Merely by scaling the length of one curve is insufficient because the spacing between matching points on the two curves is not always proportional[10].

Coordinated motion can be achieved by relating the parameters of position curve to those of orientation curve. Let the position vector $\boldsymbol{p}_i\,(i = 0,1,\cdots,n)$ is related to $\lambda_j\,(j = 0,1,\cdots,m)$ and $\boldsymbol{q}_i\,(i = 0,1,\cdots,n)$ is related to $w_j\,(j = 0,1,\cdots,m)$, where $w$ is the parameter of $\boldsymbol{q}(w)$. Standard-chord-length parameterization in Section 1 is operated to $\boldsymbol{q}_i\,(i = 0,1,\cdots,n)$ and a series of knots can be calculated out as $t_j\,(j = 0,1,\cdots,m)$. A cubic spline $\boldsymbol{F}(\zeta)$ will be constructed through a set of points, $\{\boldsymbol{F}_j\}_{j=0}^m = \{\lambda_j, t_j\}_{j=0}^m \subset \mathbf{R}^2$. With the same method, a cubic spline $\boldsymbol{R}(\tau)$ can be achieved through points, $\{\boldsymbol{R}_j\}_{j=0}^m = \{t_j, w_j\}_{j=0}^m$. $t_{k+1}$ can be achieved by substituting $\lambda_{k+1}$ into expression $\boldsymbol{F}(\zeta)$. And $w_{k+1}$ can be calculated by substituting $t_{k+1}$ into $\boldsymbol{R}(\tau)$.The orientation vector in next interpolation period can be calculated by substituting $w_{k+1}$ into expression $\boldsymbol{q}(w)$.

### 5.2. Kinematics transformation operation

The kinematics transformation module calculates axis positions in the next interpolation period. By taking an example that a typical tilting rotary table type 5-axis CNC machine tool which has three linear axes $X$, $Y$, and $Z$, and two rotary axes $A$ and $C$, are demonstrated the effects of the proposed tool path interpolation algorithm on the commanded motion of a multiaxis machine tool. Supposing that the position vector in the next interpolation period is $\boldsymbol{p} = [x \quad y \quad z]$ and the corresponding orientation vector $\boldsymbol{q}=[f \quad g \quad h]$, the coordinates of all axes, $X$, $Y$, $Z$, $A$, and $C$, can be calculated by

$$\left.\begin{array}{ll}\begin{cases}A=\arccos h \\ C=\arctan(-f/g)\end{cases} & \begin{pmatrix}h\neq 1 \\ \sin A\neq 0\end{pmatrix} \\ \begin{cases}A=0 \\ C=0\end{cases} & \begin{pmatrix}f=g=0 \\ h=1\end{pmatrix}\end{array}\right\} \tag{4}$$

$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}=\begin{bmatrix}\cos C\\-\cos A\sin C\\\sin A\sin C\end{bmatrix}x+\begin{bmatrix}\sin C\\\cos C\cos A\\-\cos C\sin A\end{bmatrix}y+\begin{bmatrix}0\\\sin A\\\cos A\end{bmatrix}z+\begin{bmatrix}0\\d\sin A\\d\cos A\end{bmatrix} \tag{5}$$

where $d$ defines the coordinates of the part relative to the machine tool in its workspace. It can be set through a button on the HMI of the controller or a configuration file.

## 6. Performance Evaluations

A CNC controller of structure shown in Fig.2 with curve interpolation function based on the introduced algorithms is developed for a 5-axis machine tool which has three linear axes $X$, $Y$, $Z$, and two rotary axes $A$ and $C$. The CNC controller works as an application program on the industrial computer, AXIOMTEK workstation (PentiumIV 3.0 GHz, RAM 1 GB). A worst-case response time of 12 μs for hard realtime transactions and an average running time of calculation in interpolation operation, 23 μs, can easily fulfill the realtime requirements set by the motion controller.

In order to implement a machining path as shown in Fig.4, the NC codes should consist of 50 segments by adopting the linear interpolation method. Fig.5 shows 10 fold amplified 26 cutter location (CL) points and the corresponding tool orientation vectors for the linear machining.

By comparison, adopting the above-introduced spline interpolation controller can reduce the size of NC codes a lot, for an NC code needs only one segment containing 11 position vectors and 11 orientation vectors if the same tool path (see Fig.4) is to be implemented. Fig.6 and Fig.7 illustrate the position spline and the orientation spline generated by the proposed algorithm.

The superiority that the curve interpolation method can reduce the size of NC files turns more obvious in high-precision machining.

To implement the path shown in Fig.4, double NURBS (DNURBS) interpolation method in Ref.[21] and the proposed spline interpolation method were separately used. The orientation errors within the circle of curvature at each interpolation point were calculated

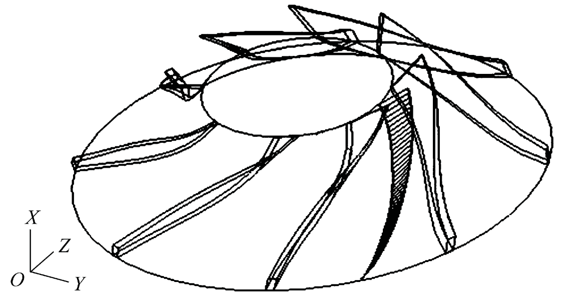


Fig.4 A machining path to be processed.

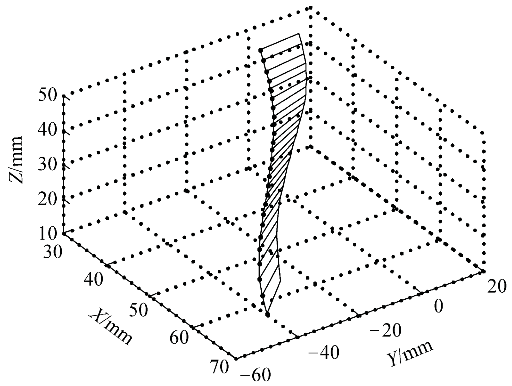


Fig.5 10 fold amplified 26 CL points and corresponding tool orientation vectors for linear machining.

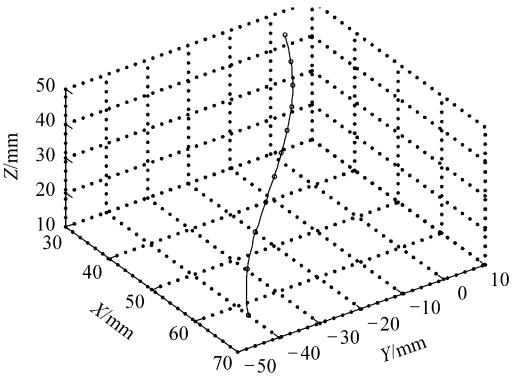


Fig.6 Position spline generated by proposed algorithm.

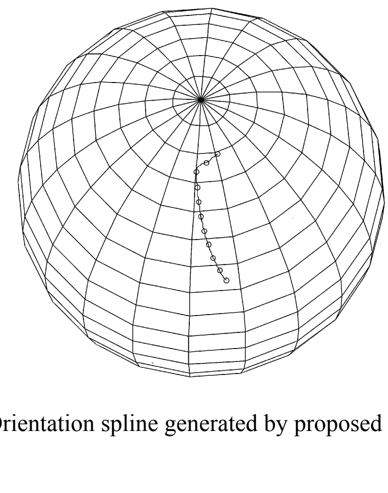

Fig.7 Orientation spline generated by proposed algorithm.

during each machining process. Fig.8 displays the error data chart thus collected, in which the heavy line describes the errors with DNURBS interpolation and the fine line with the proposed spline interpolation. In Fig.8, $\xi$ denotes the errors, and $u$ the parameter of the position.

From Fig.8, it is clear that, in implementing the path described by Fig.4, the errors produced by the proposed spline interpolation method are less than those by the DNURBS interpolation method. Moreover, the proposed spline interpolation function could greatly enhance the machining performance especially when rotation values and displacement values are way out of proportion in 5-axis machining.

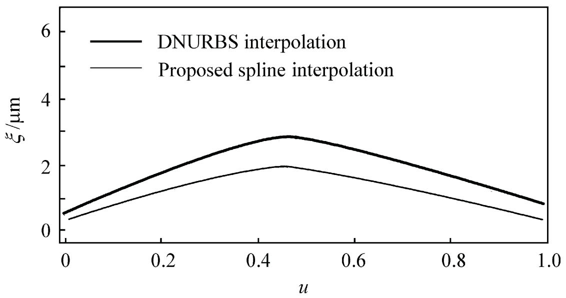


Fig.8 Errors of two methods.

Fig.9 shows a 5-axis NC milling system based on the motion controller, in which the machine tool has three linear axes $X$, $Y$, and $Z$, and two rotary axes $A$ and $C$. Fig.10 shows the photo of the finished part machined with the proposed spline interpolation method.

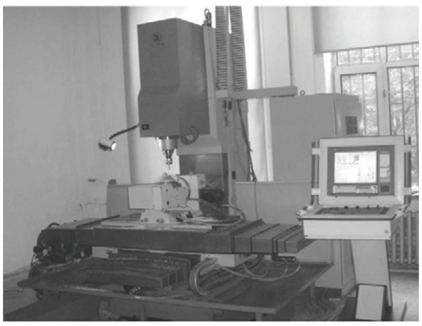

Fig.9 A 5-axis NC milling system based on motion controller.

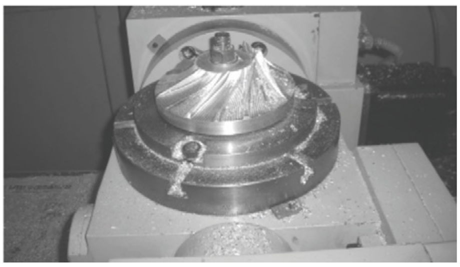

Fig.10 Photo of machined part with proposed spline interpolation method.

## 7. Conclusions

This article has proposed an open controller for 5-axis machining which adopts spline interpolation method. This controller is associated with an NC code in which the position vectors and orientation vectors are all coordinated in coordinate system of the part, as distinct from the traditional controllers which only treats information in coordinate system of machine tools. This makes programming of NC files easier.

Practices have proved that both machining accuracy and efficiency of the proposed interpolation method are superior to the linear interpolation method and DNURBS interpolation method. A solution independent of kinematics that befits the 5-axis machine tools is achieved. The controller has a bright future of being popularized into 5-axis machining.

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## Biographies:

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**Liu Yuan** Born in 1981, he received his M.S. degree from Harbin Institute of Technology in 2007, and became a Ph.D. candidate there synchronously. He focuses his research interests on open architecture CNC system, CAD/CAM, and controlling of multi-axis machining system.
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